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Technical Report

THE ROLE OF THE SKY AND LATERAL WAVES ON PROPAGATION IN FOREST ENVIRONMENTS

by

T. Tamir

(POLYTECHNIC INSTITUTE OF BROOKLYN)

March 1967

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TECHNICAL REPORT

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ABSTRACT

Propagation of electromagnetic waves in forest environments at medium and high radio frequencies is examined for the case where both the transmitting and receiving points are situated within the vegetation. A conductive slab in the presence of a reflecting ionosphere is employed to describe the forest configuration and this model is further simplified by disregarding the ground-forest interface. The radiated field of an arbitrarily oriented small dipole is found to consist primarily of two separate waves: a lateral wave which skims along the tree tops and a sky wave which is produced by a single-hop reflection at the ionospheric layer. These two field constituents are compared and their domains of preponderance are calculated for a large range of the pertinent parameters; it is then found that the lateral wave plays the major role since the sky wave is restricted to a narrow frequency band and its amplitude is appreciable only at large distances.

The lateral wave field is examined in detail and is shown to yield a simple physical picture for the propagation mechanism in forests. Its features are found to be qualitatively consistent with the field behavior reported in the literature and the quantitative aspects agree well with the available experimental data. The observed variation of the field with distance, the height gain effect, the vegetation factor, the basic path loss and depolarization effects are separately examined and are all shown to express merely one or another of the intrinsic properties of a lateral wave. The ground proximity effect produced by the presence of a planar conducting ground is also estimated and shown to be of minor importance in most cases.

ACKNOWLEDGMENTS

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FIGURES

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I. INTRODUCTION

The propagation of electromagnetic waves in forest environments has recently attracted considerable interest in view of the necessity to communicate through media which may contain considerable amounts of dense vegetation. The main difficulty encountered in those situations is that the transmission losses are substantially higher than those which occur in the absence of vegetation.

The present work is a study of the effects produced by a forest medium on electromagnetic propagation at high frequencies (1-100 Mcs.) when both the transmitting and the receiving antennas are inside the vegetation. The electromagnetic fields under those circumstances are examined for a large range of parameters which cover most practical cases. Particular emphasis is given to the wave types which are responsible for the propagation mechanism and it is shown that the energy proceeds by means of either a sky wave or a lateral wave. The latter is intimately connected with the critical angle of total reflection in geometrical optics and its field travels mostly in the air region by skimming across the tree tops. This lateral wave is shown to be effective mostly at short ranges and at the higher frequencies. The sky wave is produced by a simple reflection from the ionosphere and is found to predominate at longer ranges and at the lower frequencies.

The propagation aspects discussed in the present work are examined by regarding the forest in terms of a conducting dielectric slab which is located on a plane ground. As discussed in Section II, this representation is adequate for the range of frequencies of 1 to 100 Mcs. and for the practical distances (less than 100 kms) which usually occur in forest environments.

The slab model is further simplified by neglecting the ground proximity. The field due to a small electric dipole is then obtainable in a rather simple form which lends itself to a straightforward physical and numerical analysis.

The modifications required by the presence of the ground are also discussed and it is shown that the simplified model is sufficient to determine a large amount of information and data which agree ve well with available experimental results. In particular, the observed variation of the field (proportional to the inverse squared distance), its exponential increase with height above ground and the range where fading becomes important are all correctly predicted by the present theory based on the simplified model. In addition, reasonab good agreement is obtained for the basic path losses over the entire frequency range treated herein. Other aspects, such as polarization effects, the vegetation factor and other pertinent features are discussed and evaluated.

II. THE SLAB MODEL OF THE FOREST

The literature on high-frequency propagation in forest environments is rather sparse in both theoretical studies and experimental measurements. The paucity of available material is evident from the exhaustive recent bibliography compiled by Taylor, Posey and Hagn (1966) wherein the topic of propagation through actual vegetation constitutes only a small portion of the listed paper. Although experimental investigations were started in 1943, as reported by Herbstreit and Crichlow (1964), extensive and systematic measurements have been obtained only in the last few years by Jansky and Bailey (1965).

Many of the forest models which were proposed do not account for the electro-magnetic properties of the vegetation but assume instead a plane or curved smooth earth wherein propagation is modified by terrain irregularities (Egli, 1957), diffraction leakage (Head, 1960) or other empirically or statistically derived correction factors (Jansky and Bailey, 1965; Burrows, 1966). These models are suitable for establishing propagation criteria containing empirical parameters which are determined experimentally. However, they do not lead to a simple physical understanding of the wave mechanism which is responsible for the actual propagation process.

The first attempt to account directly for the vegetation medium seems to have been made by Pounds and LaGrone (1963) who suggested that a forest be viewed as a conducting dielectric slab. However, Pounds and LaGrone did not carry out propagation studies with their model but used it only for the purpose of determining the equivalent complex dielectric constant of the vegetation. The lossy slab concept was used by Lippmann (1965) to establish an equivalent circuit for the forest. Actual propagation in such a model was considered by Taylor (1966) who assumed that the field in the forest was produced by a sky wave reflected from the ionsphere and then by Sachs and Wyatt (1966) and Sachs (1966) who disregarded the sky wave and considered instead a lateral wave which travels along the tree tops.

The present work accepts the lossy slab concept originally proposed by Pounds and LaGrone but does not restrict it to either the lateral wave or the sky wave propagation modes. By carrying out a more inclusive analysis which accounts for both wave types, it is shown that each of these predominates within different ranges of the various parameters involved. Furthermore, the present study is not restricted to fixed polarizations or limited ranges of the forest and antenna parameters such as those employed by Taylor or Sachs and Wyatt.

The basic slab geometry is shown in Fig. 1 wherein a reflecting ionospheric layer at a height H above ground was also incorporated. The conductive slab is assumed to represent a forest with an average tree height h ; the plane geometry is adequate even for large distances $\rho = (x^2 + y^2)^{\frac{1}{2}}$, since both the sky wave and the lateral wave are only slightly affected by small amounts of curvature. The transmitter is located at a height z_o above ground and is assumed to consist of a small current dipole of moment Il which is generally inclined at an angle γ with respect to a horizontal plane. By placing this dipole on the z axis and in the xz plane, the coordinate z denotes the height of the observation (receiver) point above ground while x indicates its separation from the transmitter. This arrangement is, however, chosen for convenience only and the fields will be found at any range $\rho = (x^2 + y^2)^{\frac{1}{2}}$ rather than x alone. The forest and ground media are characterized by the complex refractive indices n and N, respectively, which are obtained from:

$$n^2 = \varepsilon_1 + i\frac{\sigma_1}{\omega\varepsilon_o} = \varepsilon_1 + i\,60\,\sigma_1\lambda_o \tag{1.a}$$

$$N^2 = \varepsilon_2 + i\frac{\sigma_2}{\omega\varepsilon_o} = \varepsilon_2 + i\,60\,\sigma_2\lambda_o \tag{1.b}$$

where $\varepsilon_{\frac{1}{2}}$ denotes relative permittivity, $\sigma_{\frac{1}{2}}$ indicates conductivity and the subscripts 1 and 2 refer to the forest and ground media, respectively; ε_o and λ_o are the absolute permittivity and the wavelength in air (vacuum)

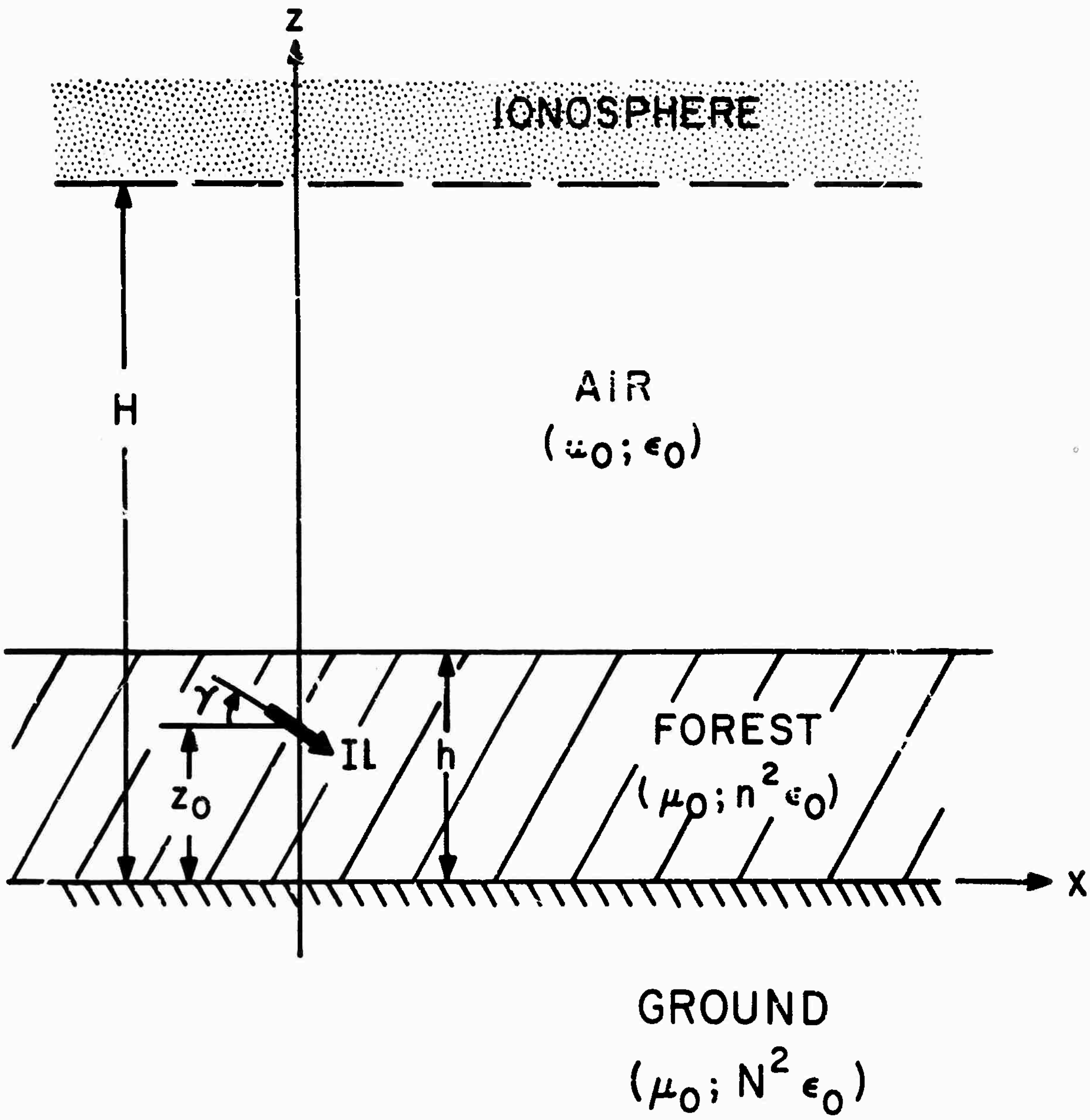


Fig. 1 - Basic geometry for the forest propagation model.

of a wave with angular frequency ω . A time dependence $e^{-i\omega t}$ is assumed and MKS units are implied unless otherwise specified.

The various parameters involved in the forest slab model are examined separately as follows.

A. THE FREQUENCY

The frequency f must be sufficiently low if the representation of the forest in terms of a uniform continuous medium is valid. In view of the average separation of trees and the fact that the space in between is usually filled with foliage and other vegetation, an upper frequency of f = 100 Mcs. (minimum wavelength of λ_0 = 3 m.) seems reasonable. The lower frequency end is restricted herein to 1 Mc. due to theoretical considerations described in Section III and in the Appendix.

B. THE RANGE OF OBSERVATION

The range of observation ρ considered here is such that, in general: $\rho > 1$ km. The lower limit is prescribed by the theoretical considerations already mentioned above but, as shown in the Appendix, ρ may be considerably smaller than 1 km. at the higher frequencies. For practical reasons, the discussion will also be restricted to $\rho < 100$ kms since forests are not expected to preserve sufficient uniformity at longer ranges.

C. THE TREE HEIGHT

The tree height h is that which generally occurs in forests around the world. As catalogued in the literature (Pounds and LaGrone, 1963; Jansky and Bailey, 1965), h varies from about 1 meter (in bush lands) to 50 meters (in climax forests). Although the results herein are not restricted to these values of h , it is nevertheless implied that $h << x$. For practical reasons, the tree height h will be restricted to $h < 30$ meters in most of the following discussions since heights larger than 30 meters are seldom encountered.

D. THE FOREST PARAMETERS

The forest parameters ϵ_1 and σ_1 turn out to be rather critical and, unfortunately, only a very limited amount of data concerning their actual values are available. Certain theoretical considerations predict that $\epsilon_1 \simeq 1.1 - 1.2$ while σ_1 is of the order of 10^{-4} mho/meter (Pounds and

La Grone, 1963; Hagn and Parker, 1966). To ensure an exhaustive coverage for all possible circumstances, the ranges considered here are:

$$1.01 \leq \epsilon_1 \leq 1.5 \qquad \text{and} \qquad 10^{-3} \leq \sigma_1 \leq 10^{-5} \text{ mho/meter} .$$

These ranges extend considerably more than those found by Hagn and Parker (1966) by measurements in a large variety of forest vegetation.

The values of σ_1 must obviously lie between zero and $\sigma_v >> \sigma_1$, where σ_v represents the conductivity of the vegetative fiber which constitutes the forest. Similarly, ϵ_1 has a value between unity and $\epsilon_v >> 1$, where ϵ_v is the relative permittivity of the sap. Hence dense forests will exhibit large values for both σ_1 and $\epsilon_1 - 1$ while thin forests will yield small values for these parameters. One therefore expects that $\epsilon_1 - 1$ is roughly proportional to σ_1 in such a manner that the lower limits ($\sigma_1 = 10^{-5}$ and $\epsilon_1 = 1.01$) and the higher limits ($\sigma_1 = 10^{-3}$ and $\epsilon_1 = 1.5$) occur together. Furthermore, if it is assumed that σ_1 is frequency independent, one obtains the approximation:

$$|n^2 - 1| = |\epsilon_1 - 1 + i\, 60\sigma_1 \lambda_o| \simeq 60\sigma_1 \lambda_o, \quad (1 < f < 12 \text{ Mcs}), \qquad (2)$$

This approximation agrees with the experimental results obtained by Hagn and Parker (1966) who also confirmed that σ_1 does indeed seem to be frequency independent.

E. THE GROUND PARAMETERS

The ground parameters ϵ_2 and σ_2 are those which generally occur in the better conducting grounds, i.e.,

$$5 \leq \epsilon_2 \leq 15 \qquad \text{and} \qquad 10^{-3} \leq \sigma_2 \leq 10^{-2} \text{mho/meter}.$$

As discussed subsequently, the ground parameters have a minor effect when compared to the forest parameters, so that the former need not be accurately known.

F. THE IONOSPHERE HEIGHT

The ionosphere height H corresponds to the height of the effective reflection plane at any given frequency f. Since the lowest value of H is about 100 kms., the following inequality holds:

$$h << \ell < H , \qquad (3)$$

This inequality will be employed throughout the discussion.

Certain restrictions, as well as the possibility of extended ranges for the values of the above parameters, are discussed in the Appendix.

III. THE VARIOUS WAVE CONTRIBUTIONS TO THE FIELD

Although it is possible to obtain a solution to the far field dipole radiation for the model shown in Fig. 1, the large number of parameters and particularly the three different interfaces (at $z = 0$, h and H) lead to a result which is algebraically complicated. A considerable simplification is obtained by assuming that the ground medium possesses the same electric properties as the forest, thus leading to the simplified geometry shown in Fig. 2 . The new model is equivalent to a forest half-space rather than a slab, and is obtained by letting the ground-forest boundary recede to infinity (at $z \to -\infty$). The effect of the ground may thereafter be introduced in the half-space results by means of relatively simple modifications which are described in Section VI. It is significant, however, that the simple half-space results are adequate for obtaining a large variety of information in many practical situations.

In the simplified problem, the various contributions to the field at the observation point R are illustrated in Fig. 2 and their mathematical expressions and physical features will now be discussed.

A. THE FOREST GEOMETRIC-OPTICAL CONTRIBUTION

In the absence of an ionospheric layer, the situation shown in Fig. 2 reduces to that of a simple half-space problem. The basic waves which then appear are a direct ray and a reflected ray (as shown by the trajectories TR and TSR, in Fig. 2), and these together constitute the geometric optical contribution for that case. The electric field $E^{(F)}$ which corresponds to these waves is given in the literature (Brekhovskikh, 1960; Wait, 1962) and may be cast into the form;

$$E^{(F)} = 30 \Pi \left[f_d \frac{e^{ik_o n r_d}}{r_d} + f_r \frac{e^{ik_o n r_r}}{r_r} \right], \tag{4}$$

where $k_o = \omega \sqrt{\mu_o \varepsilon_o}$ is the wavenumber of air (vacuum), while r_d and r_r designate distances along the trajectories TR and TSR, respectively; f_d and

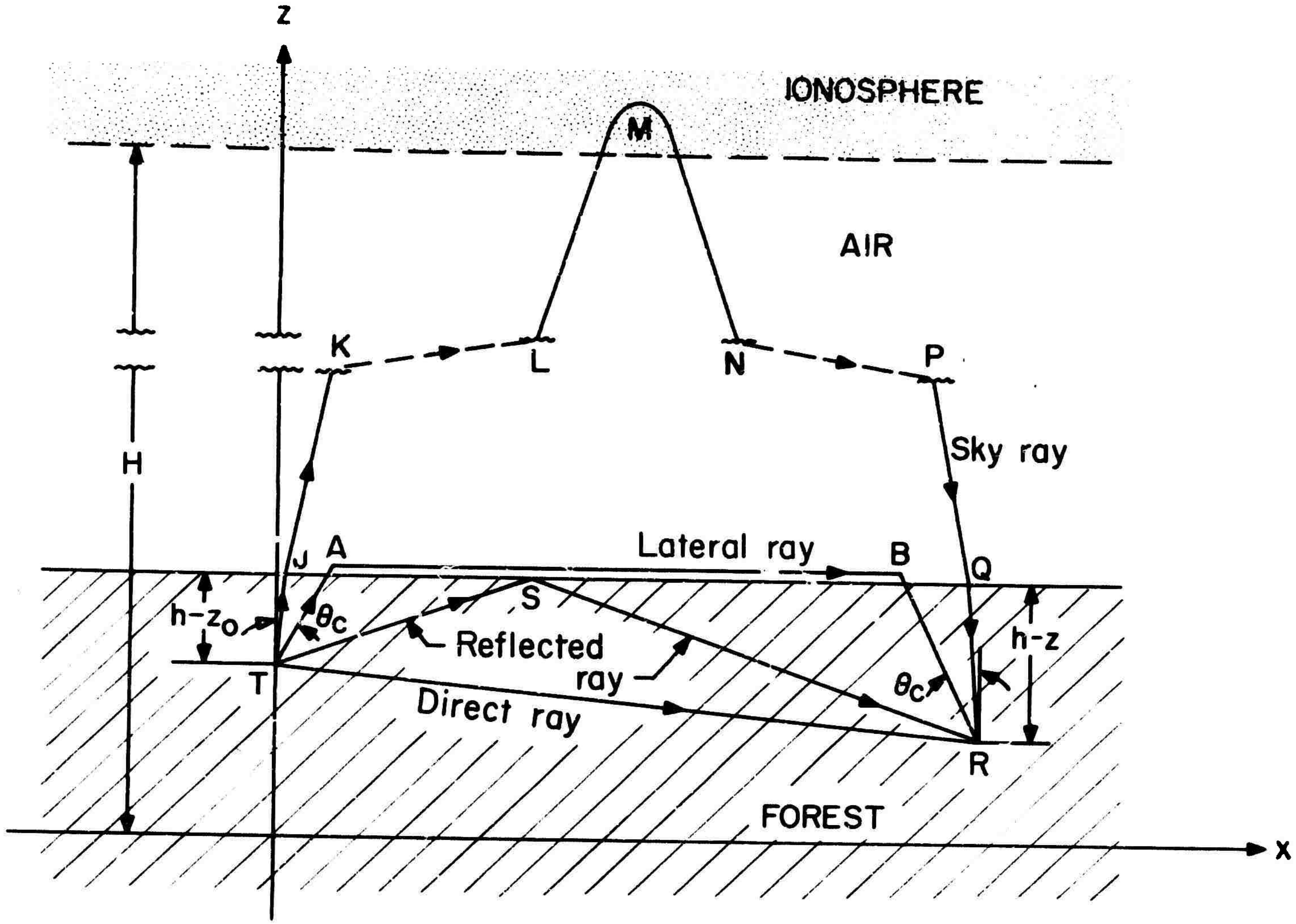


Fig. 2 - The simplified forest model and the various field contributions

f_r are, in general, functions of the inclination angle γ and the coordinates x, y, z, and the subscripts d and r refer to the direct and reflected rays, respectively. The time dependence $e^{-i\omega t}$ is implied and omitted in Eq. (4), as well as in all subsequent expressions.

B. THE SKY WAVE CONTRIBUTION

The presence of the ionospheric layer at z = H introduces another major geometric-optical contribution. This corresponds to a ray which starts at the source and is refracted into the air region; after being deflected by the ionosphere it then proceeds towards the forest where it reaches the observation point after another refraction process, as shown by the ray trajectory TJKLMNPQR. To obtain an expression for this sky wave, the ray path is simplified by assuming a perfect plane reflector for the ionosphere and by neglecting the refraction angles at the air-forest interface, as shown in Fig. 3. The latter approximation is justified by the fact that the forest refractive index n usually does not differ very much from unity; hence one may disregard both reflections and refractions when obtaining a first order result.

Consider now the sky wave component produced by the vertical component of the current dipole. By using the result for a simple spherical wave expanding from the source and progressing along the path shown in Fig. 3, one obtains an electric field at the observation point R:

$$E_z^{(S)} = 30\, \Omega\, k_o \sin\theta_i \sin\gamma \frac{e^{ik_o ns \sec\theta_i}\, e^{i[2k_o(H-h)\sec\theta_i + \frac{\pi}{2}]}}{[s + 2(H-h)]\sec\theta_i} \quad (5)$$

where θ_i is the inclination angle of the wave and

$$s = 2h - z_o - z \quad (6)$$

is the total separation of the source and observation points from the forest-air interface. It will be shown that the separation distance s is an important factor in forest propagation.

The result (5) must be improved by adding a multiplier A_i to account or ionospheric absorption losses which are strongly dependent on time , frequency and geography. One may then omit the second exponent since it represents only a phase term which may be absorbed in A_i; in addition, the condition that $H >> s > h$ is introduced to obtain:

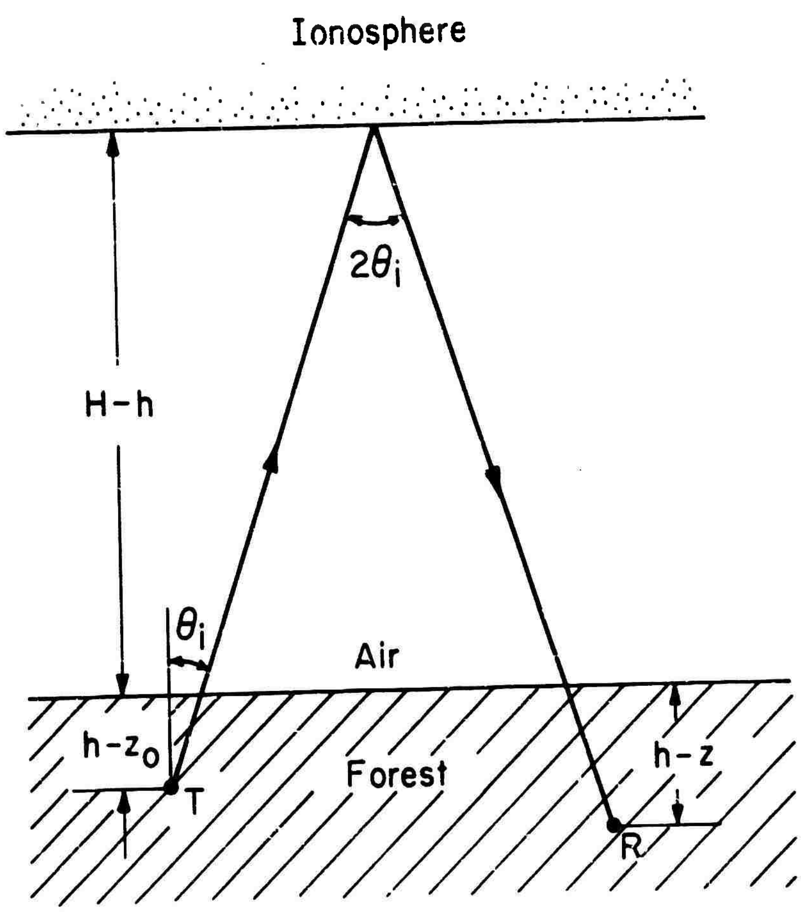


Fig. 3 - Simplified ray path for the evaluation of the sky wave.

$$E_z^{(S)} \simeq E_S \sin\theta_i \sin\gamma \, , \tag{7}$$

where

$$E_S = 15\,\Pi\, k_o\, A_i \, \frac{e^{ik_o ns \sec\theta_i}}{H \sec\theta_i} \, . \tag{8}$$

A similar calculation is easily carried out for the horizontal component of the current dipole. Due to $H >> h > z$, the field then occurs, to a first approximation, in only the x direction. This contribution is then of the form:

$$E_\rho^{(S)} \simeq E_S \cos\theta_i \cos\phi \cos\gamma \, , \tag{9}$$

$$E_\phi^{(S)} \simeq - E_S \cos\theta_i \sin\phi \cos\gamma \, , \tag{10}$$

where, for convenience, the field components are written in terms of a cylindrical coordinate system (ρ, ϕ, z) whose origin coincides with that of the rectangular system used above.

The primary sky wave contribution is therefore given by Eqs. (7) - (10). Additional contributions occur due to the reflections of the primary wave front at the air-forest interface. However, it should be observed that, in addition to the fact that the reflection coefficient at the interface is usually small, these secondary waves would have to travel at least twice the distance 2(H-h) which is traversed by the primary wave. Hence the results in Eqs. (7) - (10) are estimated to provide an excellent approximation when $n \simeq 1$. For values of n being appreciably different from unity, these results (7)-(10) yield good upper bounds for the amplitudes of the various field components. Consequently, Eqs. (7)-(10) may be regarded as optimum values that one may expect for the sky wave under all possible forest conditions.

C. THE LATERAL WAVE CONTRIBUTION

When geometric optical contributions are present, the additional diffraction fields which may then occur are usually negligible by comparison. In the present case, however, it turns out that a diffraction component provides a dominant portion of the field over a large range of the parameters involved.

The component in question is the lateral wave which may be described by the quasi-optical ray trajectory TABR in Fig. 2. This wave is produced by the radiation emitted at the critical angle of total reflection in geometrical optics θ_c which is given by

$$\sin \theta_c = \frac{1}{n} \quad . \tag{11}$$

Strictly speaking, the angle θ_c is well defined when n is real, i.e., when a lossless medium exists in the lower half-space in Fig. 2. However, the physical interpretations are still valid if the losses are small ($\mathrm{Im}\, n << |n|$) and then only the real part of n is implied in Eq. (11).

When the ray generating the lateral wave reaches the interface, it is refracted into the upper (air) medium wherein it travels tangentially while leaking energy back into the lower (forest) medium along the direction of the angle θ_c. Some of this energy therefore reaches the observation point via the path BR shown in Fig. 2. The ionospheric layer has only a vanishingly small effect since the lateral wave field decreases rapidly in the air region at large distances away from the interface. One finds, therefore, the contribution of the lateral wave in the forest by disregarding the ionosphere, so that one again deals with a single interface separating two half-space regions, as in the case of the direct and reflected rays discussed previously. This situation may be found in the literature (Brekhovskikh, 1960; Staiman and Tamir, 1966) where it is shown to yield a lateral wave in the form:

$$E_z^{(L)} \simeq E_L \left(\sqrt{n^2 - 1} \cos \phi \cos \gamma + \sin \gamma\right), \tag{12}$$

$$E_\rho^{(L)} \simeq E_L \left[(n^2 - 1) \cos \phi \cos \gamma + \sqrt{n^2 - 1} \sin \gamma\right], \tag{13}$$

$$E_\phi^{(L)} \simeq E_L \sin \phi \cos \gamma , \tag{14}$$

where

$$E_L = \frac{60\, Il}{n^2 - 1} \cdot \frac{e^{ik_0(\rho + \sqrt{n^2-1} \cdot s)}}{\rho^2} \quad . \tag{15}$$

One may easily verify that the first and second terms in Eqs. (12) - (14) correspond to the horizontal and vertical components of the current dipole, respectively. The $\simeq$ sign indicates that the above results were obtained via an asymptotic evaluation which is, however, very accurate at large distance ρ. The dependence of the lateral wave on ρ^{-2} as compared to a geometric optical variation of ρ^{-1} reflects the fact that this wave is a quasi-optical contribution only. Its more pronounced geometric attenuation is due to the continuous energy leakage across the interface along the lateral portion AB of its path.

The above completes the list of major contributions to the field and any other diffraction components are ignored since they are of lower order (Brekhovskikh, 1960). It is important to recognize, at this point, that the resolution of the total field into the waves enumerated above is justified under certain conditions which imply that the range ρ must be sufficiently large. These criteria are examined in the Appendix wherein the permissible minimum values of ρ are presented.

IV. COMPARISON OF THE LATERAL AND SKY WAVES

One expects that the various wave types discussed above are not all of the same order of magnitude everywhere, but that each of them contributes significantly in different domains. It is therefore pertinent to establish the ranges of preference for one or the other wave varieties.

The attenuation produced by the lossy forest medium affects the various waves differently. In particular, it is noted from Eq. (4) that the forest geometric-optical contribution $E^{(F)}$ contains exponential terms which. due to n being complex, produce a decay over an extended range $r_d = r_r \simeq \rho$. By contrast, Eqs. (8) and (15) show that the decay of the lateral and sky waves occurs only over a much shorter range $s << \rho$. It is therefore evident that the forest geometric-optical contribution is negligibly small compared to the other waves except possibly at very short ranges.

It is furthermore recognized that, since $h << \rho$, the reflected component in $E^{(F)}$ occurs at grazing incidence and therefore interferes destructively with the direct component. This fact, together with the increased exponential decay, justify the neglect of the forest contribution at the minimum range $\rho = 1$ km. Thus, even for small losses ($\sigma_1 = 10^{-5}$ mho/meter), the forest wave is down by at least 60 dbs compared to the lateral wave for all $\rho > 1$ km. and $f > 1$ Mc.

One is therefore left to contrast the lateral wave with the sky wave. It is then noted that the sky wave is available only at frequencies below the maximum usable frequency which, in the present case of close to vertical incidence, is equal to the critical frequency. This establishes an upper limit of about 10 Mcs. above which the lateral wave clearly predominates. Another important point is the question of the choice between the vertical or horizontal polarization components of the two waves. Since $H \geq 100$ km, the angle $\theta_i < 25.6^{\circ}$. Hence, the horizontal polarization is definitely preferable for exciting the sky wave since $\sin\theta_i < \cos\theta_i$ in Eqs. (7)-(10). The optimum conditions for the excitation of the lateral wave are not so clear. It was shown by Staiman and Tamir (1966) that an optimum inclination angle γ_m exists but, on the other hand, the improvement obtained by operating the dipole at γ_m rather than horizontally ($\gamma = 0$) is important only when $E_z^{(L)}$ and/or $E_\rho^{(L)}$ are larger than $E_\phi^{(L)}$, i.e., if $|n^2 - 1| > 1$. In the present case, $|n^2 - 1|$ is of the order of unity or less, so that $E_\phi^{(L)}$ is usually of the order of $E_z^{(L)}$ or larger, while $E_\rho^{(L)}$ is smaller. It is therefore appropriate to compare $E_\phi^{(L)}$ with $E_\phi^{(S)}$.

Noting that

$$1 < \sec\theta_i < \sec 25.6^{\circ} = 1.107,$$

one may drop the $\sec\theta_i$ terms in Eq. (8) and obtain

$$\left|\frac{E_\phi^{(S)}}{E_\phi^{(L)}}\right| = \left|\frac{E_S}{E_L}\right| = \frac{\pi}{2}\,\frac{\rho}{\lambda_o}\,\frac{\rho}{H}\,|n^2 - 1|\,A_i\,S, \tag{16}$$

where S stands for the separation factor

$$S = e^{\alpha_r s}, \text{ with } \alpha_r = \frac{2\pi}{\lambda_o}\,\mathrm{Im}\,(\sqrt{n^2 - 1} - n), \tag{17}$$

and α_r is therefore a relative attenuation factor which indicates the difference in exponential decay between the lateral and the sky waves. A plot of α_r is shown in Fig. 4 for frequencies of 1-10 Mcs. It is then noted that $\alpha_r < 0.5$ db/meter for all of the pertinent ranges of σ_1, ϵ_1 and f. Hence S is close to unity, except at the largest values of the separation parameter s .
If S 1 (i.e., the case S > > 1 is excluded), the lateral and sky contributions become equal at a distance

$$\rho_{eq} = \sqrt{\frac{2}{\pi}\cdot\frac{\lambda_o H}{|n^2 - 1|\,A_i}} \tag{18}$$

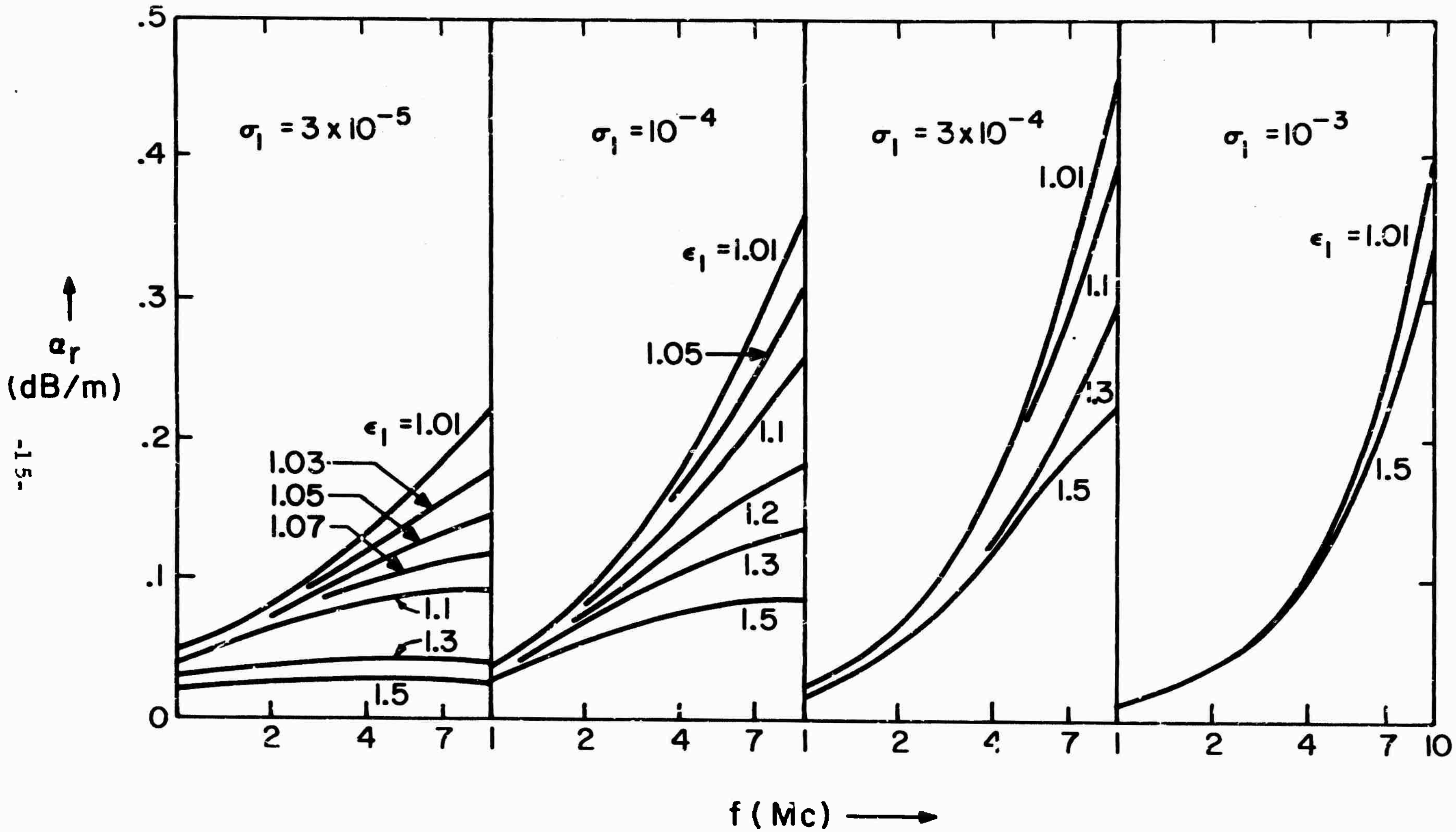


Fig. 4 - Relative attenuation α_r versus frequency, for various values of σ_1 and ϵ_1.

For large values of S, the lateral and sky wave contributions become equal at

$$\rho_{eq} = S^{-\frac{1}{2}} \rho_{eq} \quad , \tag{19}$$

where S is obtained via the curves given in Fig. 4 . One may now introduce the approximation $|n^2 - 1| \simeq 60\sigma_1 \lambda_o$ given in Eq. (2) and obtain:

$$\rho_{eq} \simeq \sqrt{\frac{2}{\pi} \, \frac{H}{60\sigma_1 A_i}} \, , \tag{20a}$$

where all quantities are in KMS units. A more convenient choice of units yields:

$$\rho_{eq} \simeq \sqrt{\frac{10^{-2} \, H}{\sigma_1 \, A_i}} \tag{20b}$$

where ρ_{eq} and H are measured in kilometers, σ_1 is given in millimhos/meter and the approximation $60\pi \simeq 200$ was also employed.

Although Eqs. (20) are simple relations, the factor A_i complicates the evaluation of ρ_{eq} because of the very large temporal and geographical variations of the ionospheric losses. To account for a sufficiently wide range, the discussion is therefore continued by considering day-and night-time conditions separately. It should be also emphasized that stable conditions are treated, i.e., reflections from the E, F_1 and F_2 layers are considered, but sporadic-E, spread-F and other effects or anomalies are disregarded.

A. NIGHT-TIME CONDITIONS

Night-time conditions prove to be the simpler case since the variation of A_i is then relatively small (3-6 dbs) and the ionospheric reflection is produced by a single (F) layer only. Depending on geography, the sun-spot cycle and other factors, one may obtain (Bullington, 1957; ITT Reference Data for Radio Engineers, 1963; Davis, 1965) the two extreme conditions described below.

1. Favorable Conditions

These occur when the ionospheric losses are least ($A_i \simeq 0.7$), the virtual reflecting height is lowest ($H \simeq 200$ km) and the sun-spot activity is high. Under these conditions, effective reflections are obtained up to

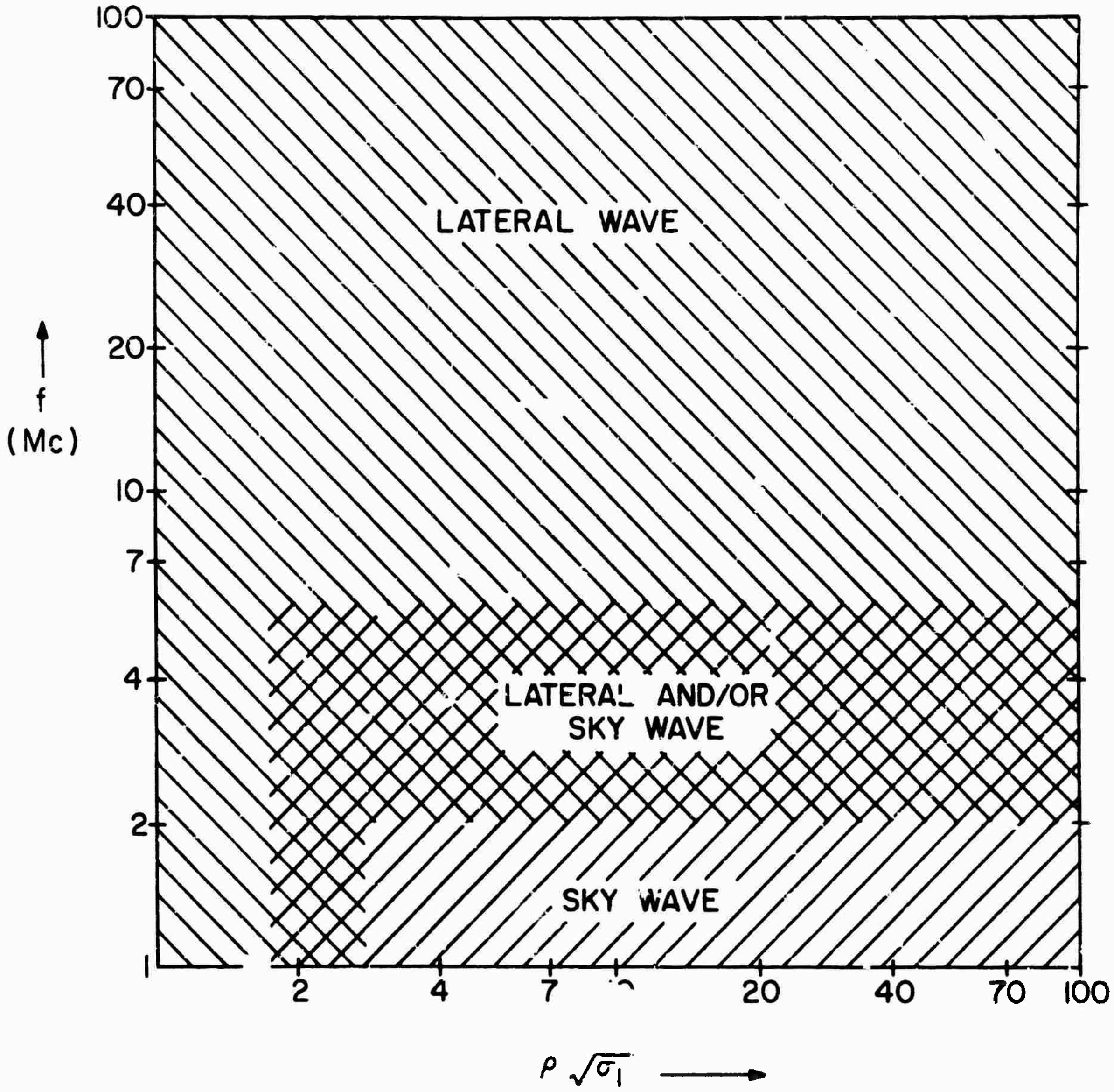


Fig. 5 - Domains of lateral and sky wave contributions during night-time regime. The units for the abscissa are: ρ in km, σ_1 in millimho/meter.

frequencies of about 6 Mcs and the sky wave then exceeds the lateral wave at distances which are larger than

$$\rho_{min} \simeq \sqrt{\frac{10^{-2} \times 200}{0.7\,\sigma_1}} \simeq \frac{1.7}{\sigma_1} . \tag{21}$$

2. Unfavorable Conditions

These occur when the ionospheric losses are largest ($A_i \simeq 0.5$), the virtual height is highest ($H \simeq 400$ km) and the sunspot activity is low. The sky wave then occurs up to frequencies not exceeding about 2 Mcs and it is dominant over the lateral wave at distances which are larger than

$$\rho_{max} \simeq \sqrt{\frac{10^{-2} \times 400}{0.5\,\sigma_1}} \simeq \frac{2.8}{\sqrt{\sigma_1}} . \tag{22}$$

The last two results show that ρ_{eq} lies between $1.7 < \rho_{eq} < 2.8$ kms and $17 < \rho_{eq} < 28$ kms in the two extreme cases ($\sigma_1 = 1$ and $\sigma_1 = .01$ millimhos/meter, respectively). A complete picture is given in Fig. 5 which shows the regions wherein either the lateral or the sky wave dominate or are comparable. It is seen therefrom that the sky wave appears to be the predominant wave only at frequencies below 2 Mcs and distances larger than ρ_{max}. Hence the lateral wave is the one that affords the more dependable contribution at distances up to ρ_{max} for $f < 2$Mcs and at all practical distances ($\rho < 100$ kms) for frequencies $f > 2$ Mcs.

These rather general conclusions may be somewhat modified by local and seasonal conditions which form stable propagation at frequencies higher than 2 Mcs. Also, the separation factor S may somewhat influence the results in favor of the sky wave provided the separation distance s is large; however, this effect will be slight for most practical cases ($s < 2h < 60$ meters).

B. DAY-TIME CONDITIONS

It is rather difficult to obtain a clear-cut comparison between the sky and lateral waves during day-time conditions due to exceedingly large variations of the parameters A_i, the maximum usable frequency (MUF) and the virtual height H. One may nevertheless consider two extreme situations which are somewhat analogous to the favorable

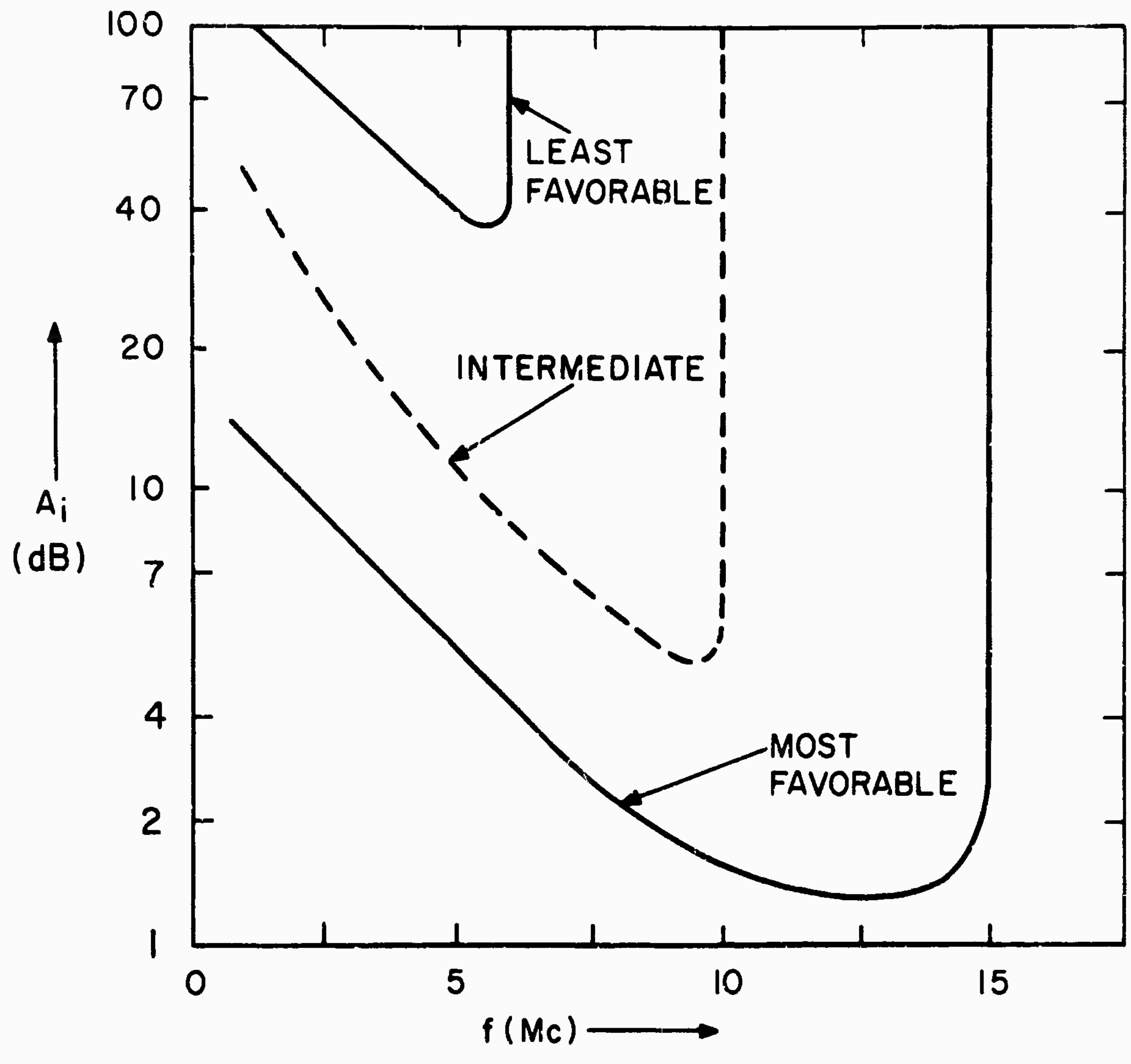


Fig. 6 - Ionospheric absorption A_i versus frequency f under various day-time propagation conditions.

and unfavorable conditions discussed above for the night-time regime. These extreme conditions cover a very wide range of possible situations and they are pertinent for all but rarely encountered variations of the "quiet" ionosphere (Davis, 1965, Chapter 3.3).

The ionospheric losses for the two extreme conditions are given in Fig. 6 where the curves with the lowest and highest losses correspond to the most favorable or unfavorable situations, respectively. The maximum usable frequencies are assumed to be 6 and 15 Mcs, respectively; these are also indicated in Fig. 6 by letting A_i become infinite at the appropriate frequencies. The virtual height H was taken, for simplicity, to vary linearly in the form

$$H_{km} = 75 + 25\, f_{Mc} \,. \tag{23}$$

Although this approximation is poor, the error that is introduced by using Eq. (23) when calculating ρ_{eq} is considerably less than the error introduced by the uncertainty in the actual value of A_i.

Inserting the values of A_i into Eq. (20) and using Eq. (23) leads to the values of ρ_{min} and ρ_{max} which are incorporated into the diagram shown in Fig. 7. When this diagram is compared with the analogous night-time situation shown in Fig. 5, it is evident that the domain wherein the lateral and the sky wave contributions may possess comparable magnitudes are considerably more extensive during day-time. This is, of course, due to the considerably larger variations of A_i in the latter case.

To obtain a better quantitative picture for any one particular situation, it is necessary to use the appropriate values of A_i for that specific case. As an example, Fig. 8 shows the curve separating the sky-wave regime from the lateral-wave regime for an ionospheric absorption variation which is typical during mid-day at temperate latitudes (see the dashed line in Fig. 6). The data in Fig. 8 correspond to a value of σ_1 = 0.1 millimho/meter which is representative of moderately dense forests. The results then indicate that the sky wave becomes predominant only at distances larger than about 10 kms. Even then, the sky wave is truly effective at intermediate distances (10-40 kms) and frequencies $2 < f < 10$ Mcs only.

The above considerations show that, although its frequency

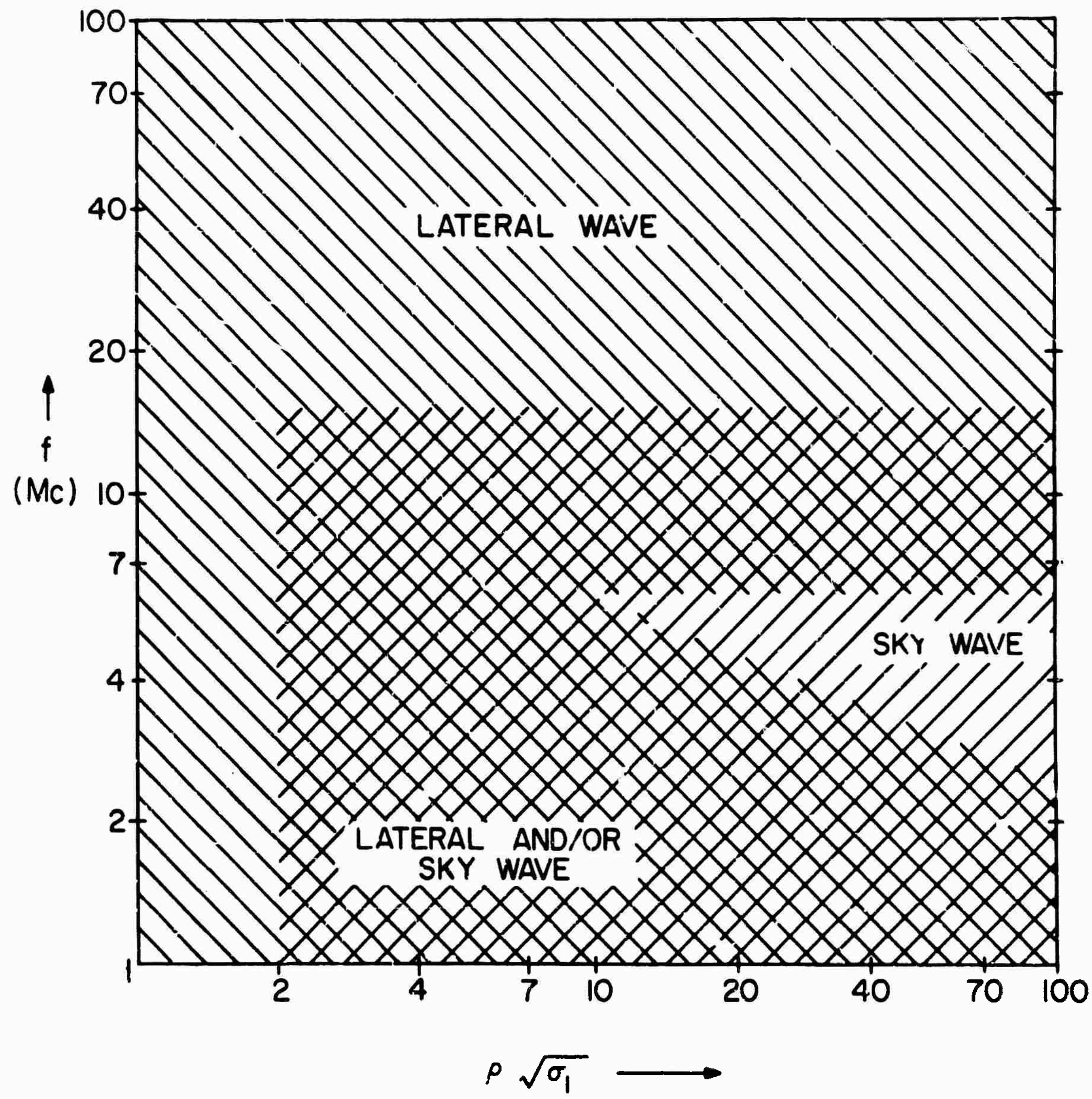


Fig. 7 - Domains of lateral and sky wave contributions during day-time regime. The units for the abscissa are: ρ in km, σ_1 in millimho/meter.

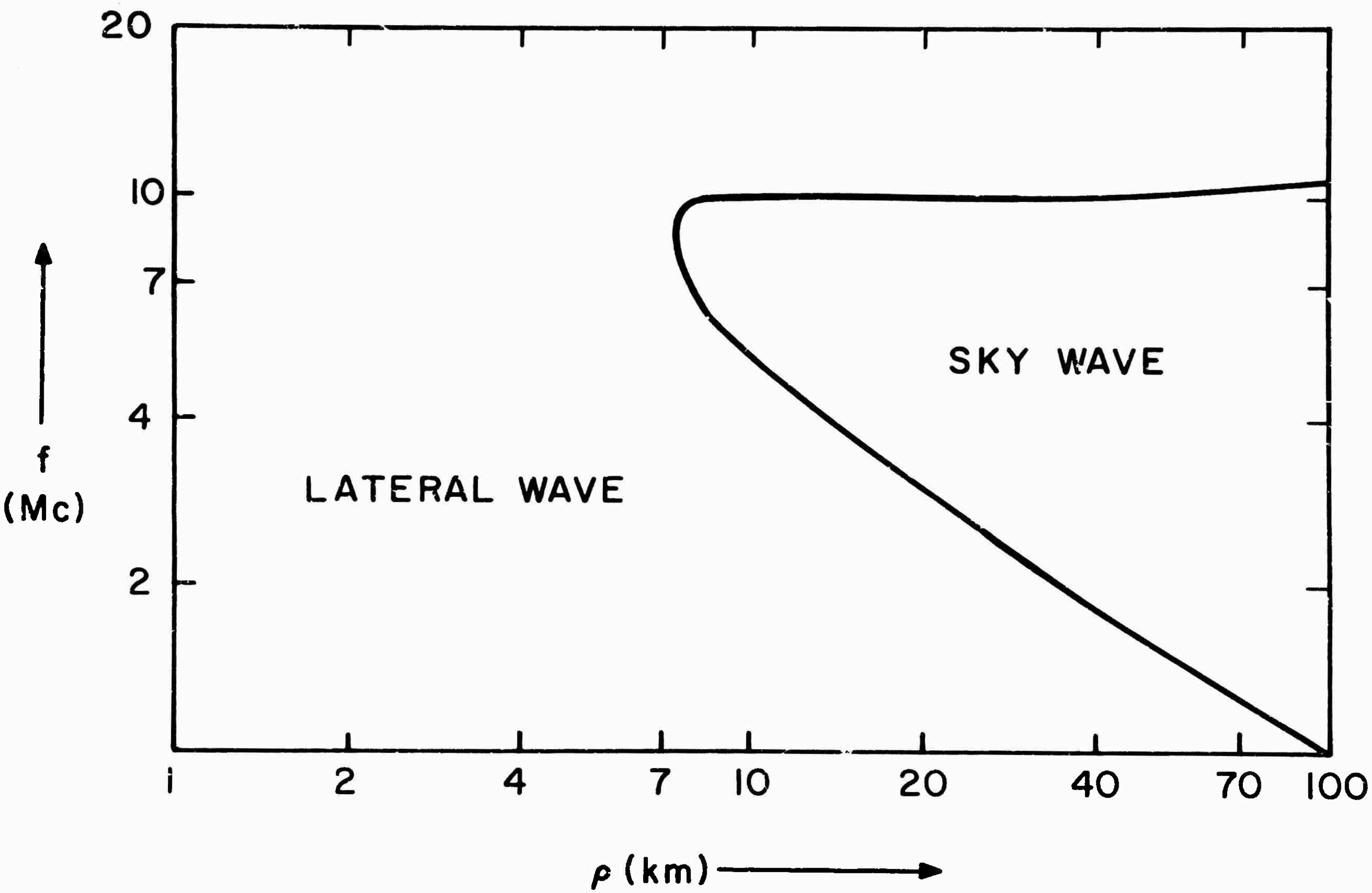


Fig. 8 - Typical day-time domains of sky and lateral wave contributions in temperate zones. Ionospheric conditions are assumed average and $\sigma_1 = 10^{-4}$ mho/meter.

range is wider during day-time, the sky wave may be stronger than the lateral wave only at distances which exceed a value of $\rho_{min} \simeq 2\sigma_1^{-\frac{1}{2}}$ kms, where σ_1 is measured in millimhos/meter. However, adverse ionospheric conditions may considerably affect this value and ρ_{eq} may then occur at a distance which is larger by one order of magnitude or more. This would exclude any significant contribution via the sky wave, except within a narrow range of values which is given by the triangular region in Fig. 7. In particular, it should be noted that $\rho > 10$ kms for that region and, if $\sigma_1 = 0.01$ millimhos/meter, the pertinent value becomes $\rho > 100$ kms.

V DISCUSSION AND COMPARISON WITH EXPERIMENTAL DATA

The results of the preceding chapter show that, except for certain restricted range wherein the sky wave may be dominant, the field in a forest model of the type considered here is primarily in the form of a lateral wave, as given in Eqs. (12)-(15). In particular, the intensity of this field is characterized by Eq. (15) which yields a magnitude

$$|E_L| = \frac{60\,\Pi}{|n^2-1|} \cdot \frac{e^{-\alpha_L \rho}}{\rho^2} , \tag{24}$$

where,

$$\alpha_L = \frac{2\pi}{\lambda_o} \, \mathrm{Im} \sqrt{n^2-1} , \tag{25}$$

and α_L refers to the exponential attenuation factor produced by the presence of vegetation.

It is pertinent to study the behavior of $|E_L|$ and to compare its functional variation with that obtained in the available experimental data. The various properties of the lateral wave are therefore examined separately in the following sections.

A. DISTANCE LOSS

The variation of the lateral wave with distance is in the form $|E_L| \sim \rho^{-2}$. Such a distance dependence produces a greater path loss than that of a geometric optical variation of ρ^{-1}, but the larger loss is expected since the lateral wave is essentially a diffracted field. The predicted ρ^{-2} variation was recently verified by the extensive measurements carried out in the Thailand jungles. In a report on those measurements (Jansky and Bailey, 1965), the ρ^{-2} variation is confirmed for both polarizations within the entire range of 1-100 Mcs. It is pertinent to note also that, in the above mentioned report, the ρ^{-2} dependence is accepted as a hypothesis deduced from the experimental data rather than a result obtained by an analytic approach.

Perhaps the most interesting feature which emerges from the measurements reported by Jansky and Bailey (1965) is that the geometric ρ^{-2} loss is obtained up to distances of 20 miles, even though the intervening terrain was very irregular. In fact, the site that was used for obtaining data contained many hills with peaks of the order of 1000 feet which precluded any direct straight paths such as the one shown for the lateral ray AB in Fig. 2. Although that situation would seem to be very adverse to a lateral wave mechanism, the results actually show that no deterioration occurs. The explanation to this eff , is that the lateral wave propagates by skimming across the tree tops and it is therefore capable of following the forest contour even though the tree-top line is curved rather than straight. Obviously, one would then need a radius of curvature which is large compared to wavelength, otherwise the lateral wave will be scattered too much and lose its consistency.

The above property of the lateral wave is of sufficient interest to be further pursued. In particular, since the possibility of curved paths is substantiated, it would be useful to further explore this aspect and find the largest irregularity allowed in the intervening terrain which still permits a ρ^{-2} variation.

Another interesting aspect of the Thailand jungle measurements is that the ρ^{-2} dependence was confirmed up to distances as short as 0.2 mile. It is recalled that the lower limit of 1 km taken in the present analysis is due to limitations imposed at short ranges by certain assumptions involved in the field representation discussed in Chapter III (see also Appendix). The experimental results indicate therefore that the lower limit may be smaller.

B. THE VEGETATION FACTOR

The presence of vegetation affects E_L via the factor

$$F_v = |n^2 - 1| \, e^{\alpha_L s}, \tag{26}$$

since the refractive index n is a function of the forest parameters σ_1 and ϵ_1. Due to the separation distance s appearing in the exponential term, the height of the vegetation above both the radiating dipole and the observation point is rather important.

It is interesting to observe that the vegetation filling the space between the transmitter and receiver has no effect apart from providing a structure which guides the lateral wave along. This property was also confirmed by the Thailand measurements (Jansky and Bailey, 1965). As in the case of the ρ^{-2} dependence discussed above, Jansky and Bailey and thereafter Burrows (1966) need to assume by hypothesis that a "foliage factor" introduces a path loss which is independent of the distance ρ. However, the lateral wave mechanism easily explains the physical nature of this effect since, as seen in Section III the vegetation introduces losses only along the ray segments TA and BR which are independent of the range ρ. The range variable ρ essentially appears in the ray segment AB which occurs in the air medium and is therefore not affected by the foliage conductivity.

The vegetation factor aspect indicates that the lateral wave mechanism is preferable to the model proposed by Burrows (1966) who explains the ρ^{-2} variation of the received field in terms of the interference between a direct ray and a ground-reflected (geometric optical) ray which connect the source and observation points. To complete his model, Burrows postulates a foliage factor F_j which he assumes to be independent of distance; however, such a ray model actually require an exponential decay with distance similar to that of the forest geometric-optical contribution $E^{(F)}$ discussed in Chapters III and IV. By contrast, the lateral wave model discussed here yields a simple explanation for the observed vegetation effect which is also wholly compatible with the other physical aspects of the propagation mechanism.

The functional dependence of the vegetation factor F_v on the separation distance s and the frequency f is examined further below.

C. THE HEIGHT GAIN EFFECT

The dependence of $|E_L|$ on the antenna height is given in Eq. (24) by exp $(\alpha_L s)$. Hence one obtains enhanced field values if the antenna elevation is increased (i.e., s is decreased). This behavior, already ascertained in the earliest experimental work (Herbstreit and Crichlow, 1964) and more recently reconfirmed (Jansky and Bailey, 1965) is referred to as a height gain.

The lateral slab model yields a simple explanation for this effect since a height increase impiies that the path length of the lateral wave in the lossy medium is reduced, i.e., the segments TA and BR in Fig. 2 are shortened. Hence the total path loss is decreased and thus leads to a corresponding path gain. This gain is characterized by α_T which takes on the values given by the various curves in figure 9.

The exponential variation of the height gain effect is in agreement with the experimental results. Jansky and Bailey (1965) concluded, on the basis of extensive measurements, that the height effect is either in an exponential ($e^{\alpha s}$) or in a logarithmic (log αs) form. If, however, one excludes their data which refer to very low antenna heights, the exponential form yields a better fit. The departure of the low-height data from the exponential variation predicted by the lateral wave probably is due to the effect of the ground proximity. Since the latter effect is not accounted for in the present model, one is justified in considering only those data which refer to antennas that are sufficiently elevated above the ground and the correspondence between the theoretical and measured variation is then very good.

As a further corroboration of the above experimental verification, it is noted that α_L in Eq. (25) is easily determined if both ϵ_1 and σ_1 are known. In the case of the Thailand jungle wherein Jansky and Bailey carried out their measurements, it was found at the higher frequencies (50-100 Mcs) that $1.05 < \epsilon_1 < 1.15$ and $0.05 < \sigma_1 < 0.15$ millimhos/meter (G.H. Hagn and H.W. Parker, private communication). Assuming that these quantities are frequency-independent, α_L as obtained from Eqs. (1.a) and (25), possesses values which lie anywhere between the two extreme curves shown in Fig. 10. Actual measured values of α_L (Jansky and Bailey, 1965) are indicated in the figure by the letters V and H which denote vertical and horizontal polarization results, respectively, and the indicated points represent smoothed-out values obtained from a large amount of similar measurements. It is clearly seen that all of the measured attenuation points lie well within the range of values predicted by the lateral wave model. At frequencies less than 12 Mcs, the height gain was too small to be efficiently detected. Note also that the values of $\epsilon_1 = 1.1$ and $\sigma_1 = 10^{-4}$ mho/meter yield a curve, shown dashed in

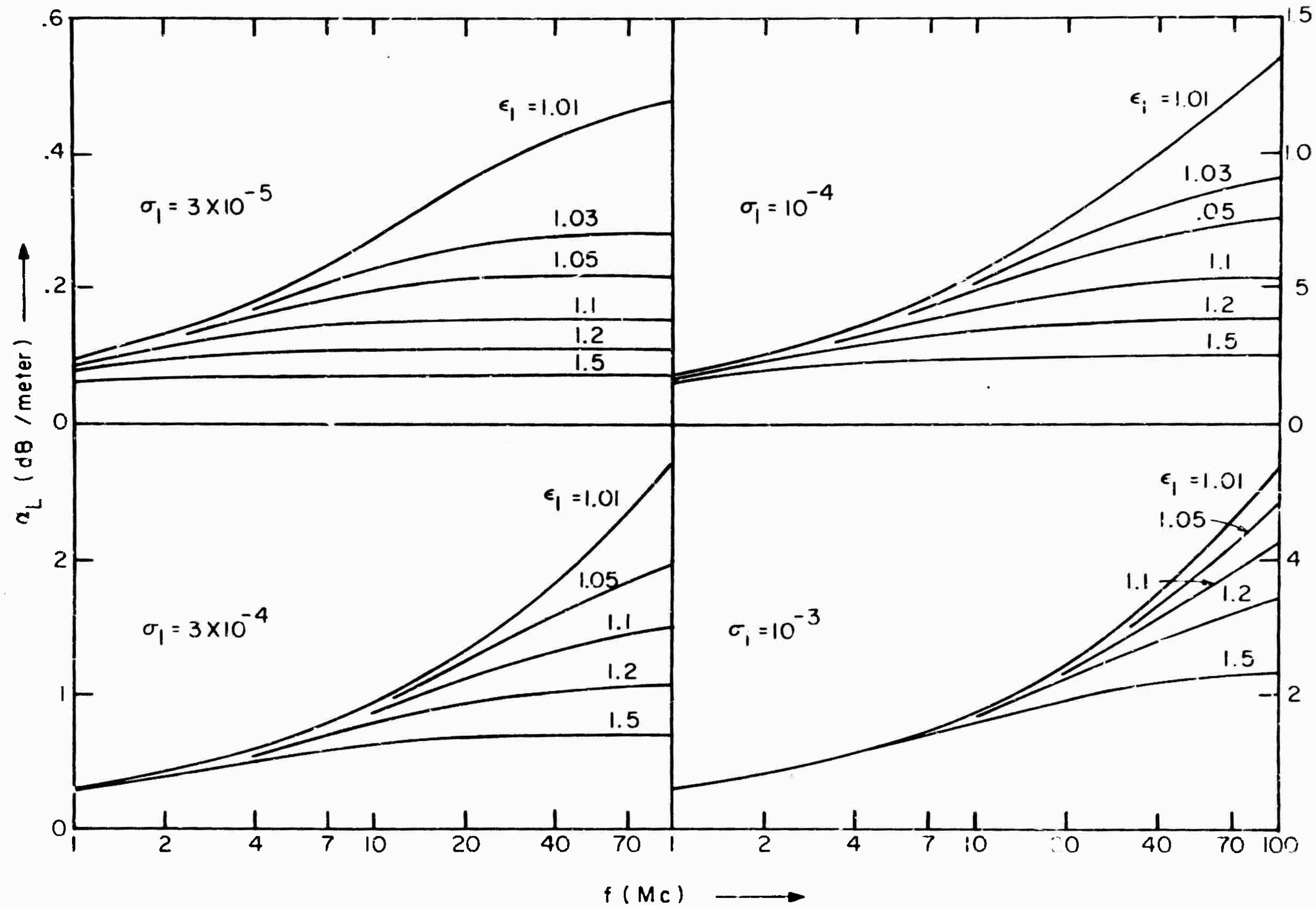


Fig. 9 - Lateral wave attenuation α_L versus frequency f for various values of σ_1 and ϵ_1. Note different ordinate scales.

Fig. 10, which gives a very good fit up to 100 Mcs. These values of ϵ_1 and σ_1 are a good average of the various data obtained by Hagn and Parker.

It is interesting to note that the comparison illustrated in Fig. 10 essentially relates two apparently independent sets of results: on the one hand, the experimental points H and V were obtained by means of field strength measurements at various antenna heights; the solid curves, on the other hand, represent theoretical predictions which are obtained by a set of completely different experimental measurements, namely those for the refractive index n . The lateral wave model enters the picture only as the tool employed for correlating the two sets of data. The consistent quantitative agreement obtained over the pertinent frequency range thus emphasizes the plausibility of the lateral wave model.

Another important aspect emphasized by Fig. 10 is that the height gain is critically dependent on the particular values of both σ_1 and ϵ_1, particularly at the higher frequencies. Thus, the two extreme cases shown by the solid curves yield attenuations which differ by 0.8 db/meter at 100 Mcs. Hence, an accurate determination of both σ_1 and ϵ_1 is important for determining the total path loss in the case of tall trees and low antennas (s large).

The differences which, as shown in Fig. 10, occur between horizontal and vertical polarizations will be discussed in Section E below.

D. FREQUENCY VARIATION AND PATH LOSS

The variation of the lateral wave field E_L with frequency is found by examining only the vegetation factor F_v of Eq. (26), since all of the other quantities do not depend on frequency. However, the result for E_L was expressed in terms of a fixed current dipole Il and it is therefore more appropriate to consider power quantities and derive the path loss L_b for the present situation.

The power available from a small dipole antenna located in the forest is given by (Jasik, 1961):

$$P_r = \frac{|E_L|^2 \lambda_o^2}{320\pi^2} \cdot \frac{1}{Re(n)} \qquad (27)$$

where the real part of n is introduced to account for the medium surrounding the dipole. Introducing relations (24 and (26) into the above .

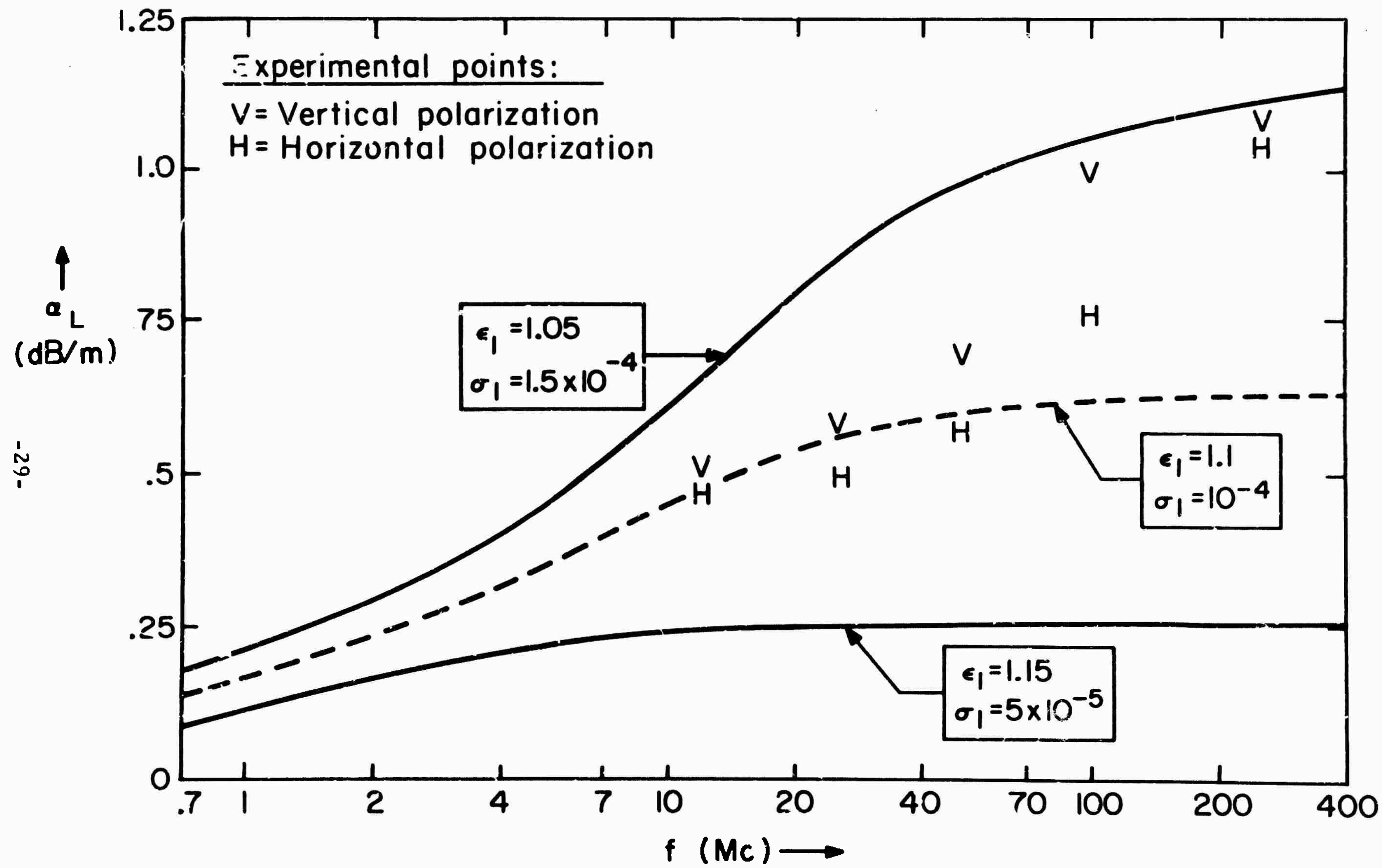


Fig. 10 - Theoretical and experimental values of the lateral wave attenuation α_L versus frequency f .

one gets:

$$P_r = \frac{45}{4\pi^2} \left(\frac{Il\lambda_o}{\rho^2}\right)^2 \frac{1}{|F_v|^2 \mathrm{Re}(n)} \tag{28}$$

The power radiated by the transmitting dipole is not so easily obtained since it generally depends on the polarization and on the dipole location h-z below the tree tops. To simplify the situation, the somewhat coarse approximation is assumed that the radiated power is that which will be produced by the dipole when placed in a boundless (forest) medium with a refractive index n . The transmitted power is then given by (Jasik, 1961):

$$P_t = 80\pi^2 \left(\frac{Il}{\lambda_o}\right)^2 \mathrm{Re}(n). \tag{29}$$

Relations (28) and (29) then yield a basic path loss:

$$L_b = \left(\frac{3}{2}\right)^2 \frac{P_t}{P_r} = \left[4\pi^2 |F_v| \mathrm{Re}(n) \left(\frac{\rho}{\lambda_o}\right)^2\right]^2 \tag{30}$$

where the factor $(3/2)^2$ accounts for the gain of the two dipoles. If both the receiving and the transmitting antennas are close to the tree tops, Eq. (30) reduces to:

$$L_{bo} = 1570 \left[|n^2-1| \mathrm{Re}(n)\right]^2 \left(\frac{\rho}{\lambda_o}\right)^4 \tag{31}$$

where L_{bo} denotes the value of L_b at $s = 0$. At the higher frequencies, the frequency dependence of n may be neglected so that L_{bo} varies as f^4. Hence the basic path loss L_b increases strongly with frequency even if both antennas are close to the tree tops. However, this situation may change if one of the antennas (or both) are sufficiently above the vegetation canopy. In that case, propagation occurs mostly by refraction or line of sight rather than via a lateral wave, but such a situation is not presently discussed.

To check the above results, relation (31) is plotted in Fig. 11 for the same range of values of n that were already considered in Fig. 10. For that range ($1.05 < \epsilon_1 < 1.15$ and $0.05 < \sigma < 0.15$ millimhos/meter), Eq. (31)

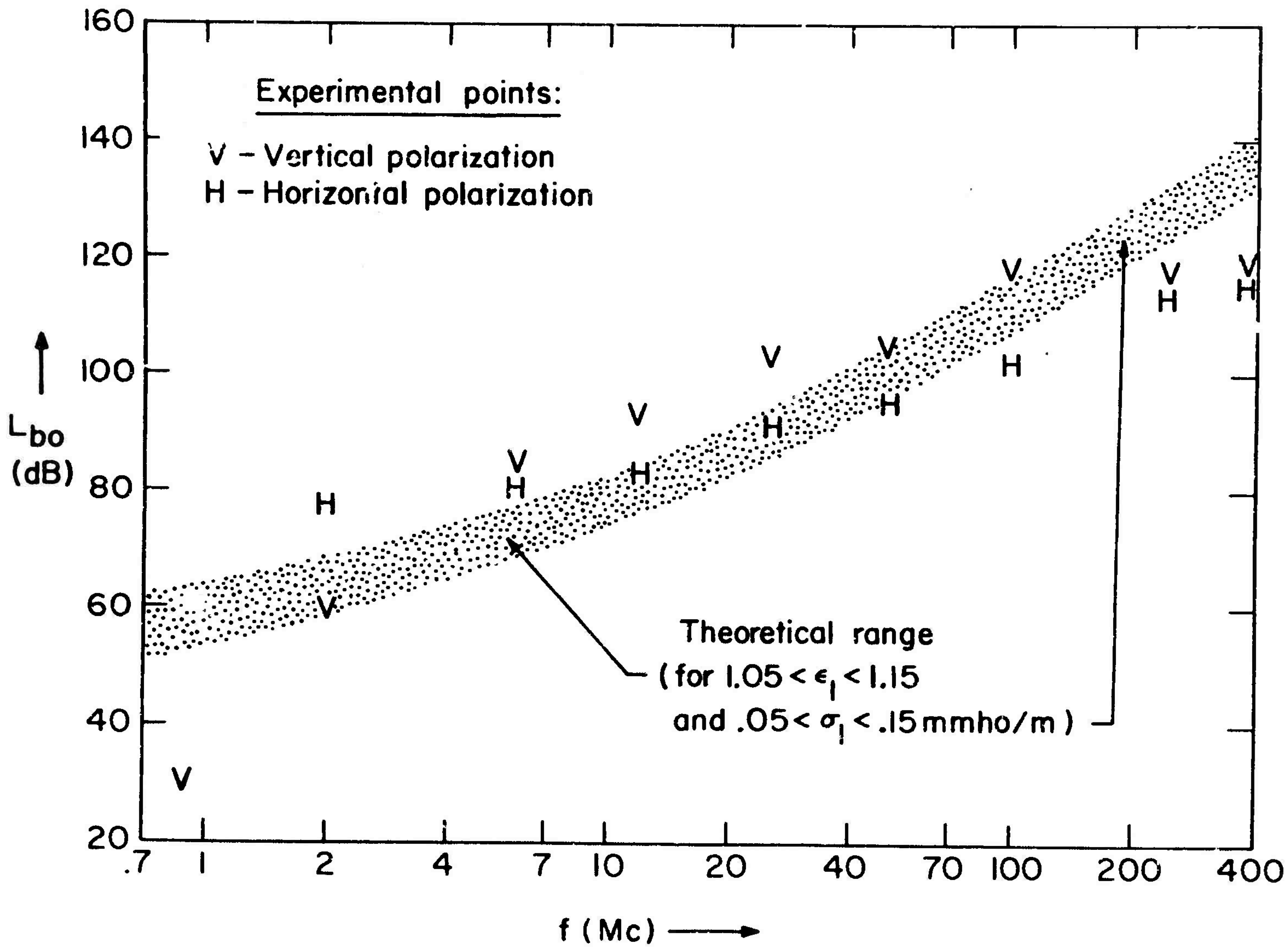


Fig. 11 - Theoretical and experimental values of the basic path loss L_{bo} versus frequency f at a distance ρ = 1 km. The theoretically predicted values lie within the shaded region.

predicts that L_{bo} is given by points which lie within the region shown shaded in the figure. Experimental results are also shown and they are indicated by the letters V or H for vertical or horizontal polarizations, respectively. These results were taken from the Jansky and Bailey (1965) report and they represent mean values of numerous measurements. Only the data pertinent to antennas located beneath the tree tops were used in Fig. 11 and the values were adjusted to account for the height gain effect by using the information supplied in Fig. 10.

An inspection of Fig. 11 shows that most of the experimental points lie within or close to the predicted shaded region. The only major exception is at 0.88 Mcs but it is recalled that the value of L_{bo} given by Eq. (31) may be quite erroneous at the lower frequencies. With this reservation in mind, it is then obvious that the agreement between the experimental and the theoretically predicted data is quite good. It is furthermore interesting to note that this agreement extends to frequencies as high as 250 Mcs. It is, however, doubtful whether the lossy slab model may be extended to these high frequencies since the vegetation is usually not sufficiently dense to be averaged out and regarded as uniform in those cases.

E. POLARIZATION EFFECTS

It is a well-known experimental fact (Herbstreit and Chichlow, 1964; Jansky and Bailey, 1965; Hagn, et al, 1966) that the signal received by an antenna located in a forest is considerably depolarized with reference to the field radiated by a transmitter situated inside or outside the forest. While this aspect could be discussed by a statistical approach which accounts for terrain irregularities (Egli, 1957), the depolarizing effect is actually predicted by the lateral wave model without necessitating any statistical considerations.

To emphasize this feature, it is recalled that the received field is not given by E_L alone but this quantity needs to be multiplied by certain factors to yield the actual field components E_z, E_ρ and E_ϕ of Eqs. (12) - (14). Thus, if one uses a vertical antenna ($\gamma = \pi/2$), a horizontal component E_ρ will be present in addition to the expected vertical component E_z, and an analogous situation holds for a horizontal dipole ($\gamma = 0$).

The above behavior is explained by noting that polarization is retained only for geometric optical contributions to the field. Thus, horizontal or vertical dipoles in free space or above a smooth ground will produce the familiar radiation patterns with well-defined polarization directions. However, the lateral wave in the forest is a diffracted field contribution and need not therefore retain the polarization of the dipole producing it.

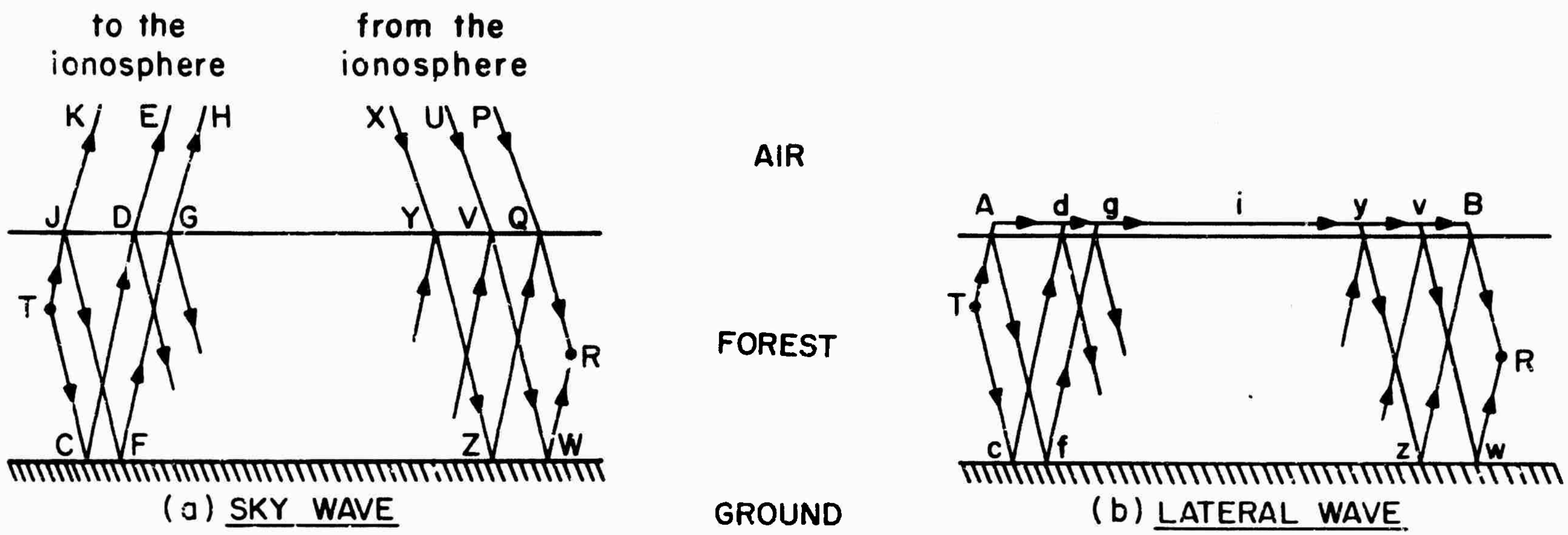
Another approach was suggested by Hagn, et al. (1966) who noted that the refractive index n is actually anisotropic since the presence of the tree trunks produces an average conductivity which is larger in the vertical direction than in the horizontal one. In that case, horizontally polarized waves would be less attenuated and this seems to be borne out by the experimental data shown in Figs. 10 and 11 for the higher frequencies (> 10 Mcs), as well as by other experiments described in the report by Hagn et al. (1966). This anisotropic effect would, however, be additional to the depolarization produced by the diffractive nature of the lateral wave.

No attempt was made in the present work to account quantitatively for the differences between the two polarizations since the half-space model does not allow for the ground proximity effect. It was felt that a more accurate path loss calculation which included polarization effects should be based on an improved model that would not neglect the presence of the ground. For the present therefore, it is only emphasized that the lateral wave mechanism implies an inherent depolarization of the radiated field, so that variations between vertical and horizontal antenna orientations are indeed expected.

[illegible]. THE ONSET OF FADING

The various features (A to E) considered so far refer to specific characteristics of a lateral wave field. A somewhat different aspect was discussed in Chapter 4 wherein criteria were obtained for ranges of preponderance for either the sky wave or the lateral wave. A comprehensive experimental verification of these criteria is not yet forthcoming since information on this question is rather scant.

A good plausible experimental indication of the range r_{eq} (where the two wave types are of equal magnitude) is given by the distance from the transmitter where fading becomes substantial. One would then surmise that the fading process would be due to interference between the lateral and the sky waves; alternatively, fading may be produced by strong variations inherent to the sky wave at a distance where the lateral wave is comparatively weak. In both cases, the range would correspond to the cross-hatched



TJK	PQR	Primary rays	TAi	iBR
TCDE	UVWR	Secondary rays	Tcdi	ivwR
TJFGH	XYZQR	Tertiary rays	TAfgi	iyzBR
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.

Fig. 12 - Ray complex for the sky and lateral waves in the presence of a reflecting ground plane.

domains shown in Figs. 5 and 7.

Some experimental evidence to the above effect is provided by Herbstreit and Crichlow (1964) who noted that fading sets in at distances between 2 and 5 kms for frequencies in the 3-6 Mcs range. Their results are consistent with the distance $\rho_{min} \sim 2\sigma_1^{-\frac{1}{2}}$ obtained in Section 4(b), provided σ_1 is close to 1 mmho/m. Since the measurements were carried out in relatively dense forests, such a large value for σ_1 is not unlikely.

Good correspondence is therefore established between ρ_{eq} derived in Chapter IV and its experimental counterpart - the distance where fading sets in. Although admittedly insufficient by itself, this feature adds credence to the lateral wave aspect of propagation.

VI. THE EFFECT OF GROUND PROXIMITY.

Since the model discussed above does not account at all for the presence of the earth plane, it is worthwhile estimating the effect of the ground on the results obtained herein.

When a ground plane is present, the forest environment is in the form of a lossy slab and the ray picture for the sky and lateral waves is then much more complex. Thus, the sky wave needs to be constructed by means of additional rays which are produced by reflections and refractions at the air-forest and forest-ground interfaces, as shown in Fig. 12(a). The diagram indicates only the first few rays and neglects any rays which are due to more than one (single- hop) reflection at the ionospheric layer. The multi-hop reflections may be disregarded since their contributions are small due to trajectories which are considerably longer than those of single-hop reflections.

Although they have different properties, the lateral waves in the lossy slab were shown (Tamir and Felsen, 1965) to yield a ray complex which is obtainable in much the same manner as that for the sky wave. In fact, the rays within the slab are ordinary geometric optical contributions which happen to be emitted and reflected at the critical angle θ_c of reflection given by Eq. (11). It is only outside the slab that the lateral wave differs from ordinary rays and, as seen in Fig. 12(b), all of the refracted portions combine there into the lateral component which skips across the interface.

For both the lateral and sky waves, the first (primary) ray of the ray complex is the one which exists when the ground is absent, as verified by comparing Fig. 2 and 12. The paths within the lossy (slab) medium of all the additional rays are longer than the path of the primary ray. Hence the additional rays will suffer a stronger attenuation and may therefore be neglected for a first approximation result. Substantial errors will then occur only in situations involving low antennas and/or low frequencies since then $z, z_o < h << \lambda_o$ and several of the additional rays may possess amplitudes comparable to that of the primary ray.

The above argument implies that the results obtained by means of the half-space model are quite general since they hold well as long as the height h is not too small compared to the wavelength λ_o. In fact, the experimental data confirm this generality since they agree quite well with the theoretical results based on the simplified model, as discussed in the preceding Chapters. It is then worthwhile obtaining a quantitative estimate for the condition $h << \lambda_o$ which limits the validity of the half-space model. For this purpose, it is noted that that the Thailand measurements (Jansky and Bailey. 1965) shown in Figs. 10 and 11 refer to a forest with an average tree height of 10 meters. Since the experimental values of L_{bo} in Fig. 11 deviate appreciably from the theoretical values only at frequencies below 3 Mcs (λ_o = 100 meters), one obtains therefore that the ground effect is feeble if $\lambda_o/h < 100/10 = 10$.

To assess the ground proximity effect when $\lambda_o/h > 10$, it is observed that only a few additional rays need then be accounted for. The complex ray picture then differs from the single ray configuration of the half-space model only at the extremities of the communication path, i.e., in the transmitter and receiver vicinity. Hence only local aspects are affected by the ground proximity if $\lambda_o/h > 10$ and these comprise the height gain effect and depolarization effects. On the other hand, the long range aspects will not be modified since the few contributing rays contain values of ρ which are essentially the same for all of them. Consequently the field dependence on ρ^{-2} and the basic path loss L_b variation of $(\lambda_o/\rho)^4$ are not affected by the ground proximity.

For the same reason, the vegetation factor F_v remains independent of ρ. However, the magnitude of F_v, as well as the value of ρ_{eq} where the lateral and sky waves are comparable, depend on a combination of both local and long range factors so that these parameters are expected to be somewhat modified by the presence of the ground plane when $\lambda_o/h > 10$.

VII. CONCLUSION

The study of wave propagation in forest environments presented here phrased the electromagnetic problem in terms of a lossy dielectric slab which characterized the vegetative medium. This slab was assumed to be bounded by a highly conducting ground and by an air region; in the latter, a ionospheric layer was also accounted for at frequencies for which ionospheric reflections are significant.

The general case of an elementary dipole embedded in the forest was examined and it was shown that the field is considerably different from that obtained in the absence of vegetation. The major factors affecting the propagation mechanism are the conduction losses of the vegetation and the presence of the forest-air interface. The ground-forest boundary seems to play only a minor role and its presence was therefore neglected.

In the first portion of the present study, the various contributions to the field were examined. It was shown that the field in the forest was given in most cases by a lateral wave which travels primarily in the air region by skimming along the tree tops. This mode of propagation is therefore very little affected by the losses in the lower (forest) medium. Nevertheless, the lateral wave is a diffracted field which varies with distance ρ as ρ^{-2}, and therefore decays more rapidly than the ρ^{-1} variation of a geometric-optical contribution in free space. Another possible contribution to the field is that of a sky wave which connects the transmitting dipole with the observation point via a single-hop reflection from the ionosphere. Although the sky wave travels a much longer distance compared to the lateral wave, the variation of ρ^{-1} of the former wave enables its field to equal that of the lateral wave at a distance ρ_{eq} of roughly 10 kms. However, in view of ionospheric absorption losses and fading, the lateral wave is usually the dependable contribution even at longer distances. Moreover, the lateral wave is practically the only significant contribution at the higher frequencies (above about 10 Mcs) for which a ionospheric reflection is excluded.

Due to its greater role, a lateral wave propagation mechanism was assumed in the remaining portion of this study. This wave variety was shown to explain many previously known features such as the height gain effect, the independence of the vegetation factor on the distance ρ and depolarization effects. In fact, it was found that the main factors affecting these aspects are the average refractive index n describing the forest medium and the separation distance s which refers to the immersion depth of the antennas below the tree line.

An interesting property of the lateral wave is that it is capable of providing a mode of propagation even when the terrain is irregular. In particular, it was observed that, since the wave follows the curvature of the tree tops, it can connect the transmitting and receiving points even if a line of sight path is obstructed by obstacles, such as small hills.

Results for the equivalence distance ρ_{eq}, the height gain effect, the vegetation factor and the path loss were presented for a large range of parameters whose extent is sufficient to cover practically all types of forests. All of these theoretical results were compared with available experimental data and good agreement was obtained. In particular, it is worthwhile to emphasize that the basic path loss was found to be proportional to $(\lambda_o/\rho)^4$ and its value, as obtained via the simplified model discussed here, agreed well with measurements over a frequency range of 2-250 Mcs.

The effect of ground proximity was also discussed and it was shown that the presence of the earth plane modifies somewhat the local properties (height gain and depolarization effects) but does not affect the long range aspects (the basic path loss dependence on ρ and λ_o, and the independence of the vegetation factor with $_o$). An investigation is presently being conducted to evaluate quantitatively the ground proximity effec and thus to establish an improved, more accurate, model for propagation studies in forest environments.

In conclusion, the present work has shown that propagation in forest environments is accounted for in most cases by a lateral wave. This wave may be adequately described in terms of a quasi-optical ray which travels mostly along the tree-top contour. In addition to its simple trajectory, the lateral wave mechanism affords a straightforward and consistent interpretation of the distance and basic path losses, the height gain effect and other physical characteristics which had already been previously established by experimental studies.

APPENDIX - EVALUATION OF NUMERICAL DISTANCES

The description of the field in terms of the various wave types discussed in Chapter III is obtained (Brekhovskikh, 1960; Wait, 1962) by an asymptotic evaluation of integrals which express the rigorous solution for the assumed dipole excitation. The resolution of the total field into the various geometric-optical contributions and the lateral wave holds only if certain parameters are large in the integrands. When that is not the case, the different contributions are not distinct but they combine into a field which may not resemble any of the wave varieties that were assumed here.

It is therefore pertinent to examine the above restrictions in order to establish the ranges wherein the present results are valid. A first condition is given (Brekhovskikh, 1960; his Eq. 20.10) by:

$$D_p = \frac{k_o \rho}{2|n|^2} >> 1 , \qquad (31)$$

where D_p is termed the "pole numerical distance". If D_p is not sufficiently large, a correction must be introduced because of the presence of a pole in the integrands of the integral expressions which represent the exact field solutions. This correction is, however, disregarded if D_p is large since then the pole is located far from the integration path and it has therefore a negligible effect.

Condition (31) is essentially a restriction on ρ since this parameter must then be larger than a certain minimum distance. To obtain an estimate for this minimum, it is convenient to examine the value of ρ which yields a pole numerical distance D_p equal to unity. If this minimum value of ρ is denoted by d_p, one has from Eq. (31) that

$$d_p = \frac{\lambda_o}{\pi} |n|^2 . \qquad (32)$$

Clearly, d_p increases with wavelength since $|n|^2$ is monotonically increasing with λ_o assuming σ_1 fixed. Hence, d_p is larger at the lower frequencies. In those cases, $|n|$ is well approximated by its imaginary part alone, so that

$$d_p \simeq \frac{60}{\pi} \sigma_1 \lambda_o^2$$

which, in view of $\sigma_1 < 10^{-3}$ mho/meter and $\lambda_o < 300$ meters, yields

$$d_p < \frac{60}{\pi} \times 10^{-3} \times 9 \times 10^4 = 1720 \text{ meters.} \tag{33}$$

Hence the minimum range $\rho = 1$ km. assumed throughout this work is quite reasonable since d_p is larger (by less than twice) only in the worst possible case. On the other hand, d_p decreases rapidly with frequency: it is less than 450 meters at 2 Mcs and about 1.5 meter at 100 Mcs. The condition for the numerical distance D_p is therefore satisfied at $\rho = 1$ km for all but unusually extreme cases.

A second restriction on the range ρ is provided by the requirement that the expressions (12) - (15) for the lateral wave be sufficiently accurate. Their validity depends on the location of a branch point which occurs in the integrand expressing the rigorous field solution. The appropriate condition is then given (Brekhovskikh, 1960; his Eq. 22.12) by

$$\eta^2 = \left|\sqrt{2k_o n\rho} \quad \sin\tfrac{1}{2}\,(\theta_c - \pi/2)\right|^2 >> 1, \tag{34}$$

where θ_c is the critical angle of reflection already given in Eq. (11). Using the latter equation one has

$$\sin\tfrac{1}{2}\,(\theta_c - \tfrac{\pi}{2}) = \frac{1}{\sqrt{2}}\left(\sqrt{\frac{1+\cos\theta_c}{2}} - \sqrt{\frac{1-\cos\theta_c}{2}}\right)$$

$$= \tfrac{1}{2}\left(\sqrt{1 + \frac{\sqrt{n^2 - 1}}{n}} - \sqrt{1 - \frac{\sqrt{n^2 - 1}}{n}}\right).$$

Noting that $|(n^2 - 1)^{\frac{1}{2}}/n|$ is less than unity and is usually quite small, one may use the binomial expansion and retain first non-vanishing terms only. One then obtains

$$\sin\tfrac{1}{2}\,(\theta_c - \tfrac{\pi}{2}) \simeq \frac{\sqrt{n^2 - 1}}{2n} \tag{35}$$

Introducing result (35) into Eq. (34), one gets a "branch numerical distance" D_b which needs to satisfy

$$D_b = \frac{k_o\rho}{2}\left|\frac{n^2 - 1}{n}\right| >> 1. \tag{36}$$

Taking d_b as the distance ρ where $D_b = 1$, one has that

$$d_b = \frac{\lambda_o}{\pi} \left| \frac{n}{n^2 - 1} \right| . \tag{37}$$

It is easy to verify that d_b increases with λ_o but decreases with ϵ_1 and σ_1. One may therefore take $|n| \simeq 1$ and use approximation (2) for the lower fequencies to obtain:

$$d_b \simeq \frac{\lambda_o}{\pi} \cdot \frac{1}{60\sigma_1\lambda_o} \quad \frac{1}{60\pi \times 10^{-5}} = 530 \text{ meters}. \tag{38}$$

Consequently, the strongest requirement for D_b is also at the lower frequencies but is less stringent than that for D_p discussed above. It then turns out, however, that restriction (36) is stronger than (31) at the higher frequencies. Thus, at 100 Mcs., d_b equals about 94 meters in the worst case ($\epsilon_1 = 1.01$ and $\sigma_1 = 10^{-5}$ mho/meter).

In conclusion, the minimum range of 1 km for ρ is quite adequate, except possibly at the lowest frequencies and the largest values of σ_1. On the other hand, the minimum range may be reduced to about 100 meters for the more often-encountered values of n ($\epsilon_1 \simeq 1.1$ and $\sigma_1 \simeq 10^{-4}$ mho/meter), especially at the medium and high frequencies (10-100 Mcs).

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Propagation of electromagnetic waves in forest environments at medium and high radio frequencies is examined for the case where both the transmitting and receiving points are situated within the vegetation. A conductive slab in the presence of a reflecting ionosphere is employed to describe the forest configuration and this model is further simplified by disregarding the ground-forest interface. The radiated field of an arbitrarily oriented small dipole is found to consist primarily of two separate waves: a lateral wave which skims along the tree tops and a sky wave which is produced by a single-hop reflection at the ionospheric layer. These two field constituents are compared and their domains of preponderance are calculated for a large range of the pertinent parameters; it is then found that the lateral wave plays the major role since the sky wave is restricted to a narrow frequency band and its amplitude is appreciable only at large distances.

The lateral wave field is examined in detail and is shown to yield a simple physical picture for the propagation mechanism in forests. Its features are found to be qualitatively consistent with the field behavior reported in the literature and the quantitative aspects agree well with the available experimental data. The observed variation of the field with distance, the height gain effect, the vegetation factor, the basic path loss and depolarization effects are separately examined and are all shown to express merely one or another of the intrinsic properties of a lateral wave. The ground proximity effect produced by the presence of a planar conducting ground is also estimated and shown to be of minor importance in most cases.

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